NOTES

Research in Ground-Water Hydrology in Hawaii

(Published with the approval of the Director as Paper No. 24 in the Journal Series of the Experiment Station, Hawaiian Sugar Planters' Association, Honolulu, Hawaii.)

Some 200 billion gallons of water a year are drawn directly from ground-water sources for the supply of plantations, factories, and homes in Hawaii (Davis, 1952, U. S. Geol. Survey, Water-Supply Paper 1161: 152). A similar amount is drawn indirectly by way of surface streams whose low flows, those of maximum value, are derived from natural springs. It is not surprising, in view of the magnitude of this draft and its vital importance to the economy of Hawaii, that a considerable amount of study has been devoted to the ground-water geology and hydrology of the Hawaiian Islands.

It is obviously true that the study of geology is necessary to the understanding of the hydrology. Lithology and structure are only geologic terms describing the same features as aquifers and aquicludes and their geometry. It is also true, though perhaps not so obvious, that the hydrology can be treated like other geophysical and engineering techniques of exploration to assist in the development of geologic understanding.

Hawaii is fortunate, first, in having complete coverage by U. S. Geological Survey topographic maps on a scale of 1/62,500 with contour intervals of 50 or 100 feet, based on field mapping on scales of 1/31,680 or 1/20,000 with contour intervals of 10 or 20 feet. In some areas, the older mapping, dating from 1910, is proving inadequate, and a current program of remapping in greater detail by aerial photographic methods is under way.

Hawaii is fortunate, second, in having the results of a survey of the geology of each of its islands, largely the result of the work of H. T. Stearns of the U. S. Geological Survey and Hawaii Division of Hydrography (Stearns, Vaksvik, Macdonald, Davis, and Cox, 1935–47, Hawaii Div. Hydrog. Bul. 1, 2, 5, 6, 7, 9, 11, 12, Bul. 13 in prep.). In some areas of the Islands where the structure is relatively simple and the hydrologic problems not severe this work may be regarded as sufficient for the understanding of the hydrology. In other areas, the stringency of the hydrologic problems requires still more detailed work of the kind done by C. K. Wentworth for the Honolulu Board of Water Supply (Wentworth, 1951, Geology and Ground-Water Resources of the Honolulu-Pearl Harbor Area).

The results of such detailed investigations are generally available through the Experiment Station of the Hawaiian Sugar Planters' Association, the Honolulu Board of Water Supply, the outer island waterworks boards, etc. In areas of complex geology, much of the extra detail may still be provided by the standard methods of field geology, although the utility of these methods will depend on the state of progress of the current program of topographic revision. More of the extra detail must come from geophysical and engineering exploration.

The principal structural elements of a typical Hawaiian island are shown in Figure 1. The largest element is a shield or dome composed predominantly of lava flows, initially of basalt but grading in the later flows to andesite, and having as a result a thinner-bedded, more porous, and more permeable interior than exterior. These flows were erupted from fissures in linear or tripartite rift zones, fissures that were left filled with lava, forming dikes. Interbedded with the flows are a few ash beds. At the center of the dome, there may be a caldera that is either partially or completely filled with flows thicker and more compact than those on the flanks by reason of their ponding. The various islands are composed of one to five volcanic domes apiece. These domes exist in various stages of erosional destruction, from Mauna Loa and Kilauea, still active and uneroded, to Kauai, much eroded and with much added complexity. After major erosion, there may have been a late series of eruptions which formed new vents and flows, the latter being thicker and more compact than the flows of the dome because of the restriction of their movement in the eroded topography. With the progress of erosion there is simultaneous sedimentation, with the deposition of both terrestrial and marine sediments along the shores of the island and in valleys submerged by changing relative sea levels.

The precipitation which falls on these volcanic domes is divided into the usual three parts, evapo-transpiration, runoff, and infiltration. Because of the high average permeability of the lava flows making up the bulk of the domes, the ratio of infiltration to rainfall is relatively high. The water descending through the rocks may accumulate in three principal types of ground-water bodies: (1) bodies perched on ash beds or soils interbedded with the flows, on conglomerates, on unconformities, or on other rocks of low dip less permeable than the average lava flows; (2) bodies impounded between the dikes that have intruded the lava flows; and (3) bodies floating on salt water. The occurrence of these bodies is diagrammed in Figure 2.

The perched and dike springs representing the natural discharge from the first two types of ground-water bodies are of great importance in providing the largest part of the low water flow of most Hawaiian streams which, without them, would be almost without value as sources of water supply. Partly through wildcat experiment and partly through knowledge of the causes of retention at high levels, the natural surface discharge from many of these perched and dike-retained bodies has been artificially increased, steadied, or diverted to economic advantage.

The qualitative relationship between the perched ground water and the ash, soil, and conglomerate beds upon which it is held was first clearly understood in 1920 through the work of W. O. Clark (Stearns and Clark, 1930, U. S. Geol. Survey, Water-Supply Paper 516) who spent many years thereafter planning and guiding development of high-level water of this sort for the sugar plantations and other agencies of the Islands. Further development is still in progress and still requires detailed geologic and hydrologic advice. An attempt to generalize quantitatively on the results expectable from this type of development would be useful in engineering future developments but would be difficult because of the high variability of the perching members in their area, thickness, continuity, permeability, and slope, and because no adequate theory exists covering nonsteady flow conditions in this kind of body. The development of such theory would seem to be easier in continental areas where experimental work could be done in perched bodies with less variability.

The understanding of the relation between dikes and the high-level water impounded between them seems to have developed gradually as a result of the construction of a number of tunnels, penetrating saturated compartments between dikes, notably the Waiahole tunnel that was driven through the Koolau Range of Oahu to transport stream water from the windward to the leeward side. The gross effects of these tunnels in draining off water stored between the dikes were early noted, but the length of time necessary to the restoration of equilibrium conditions was not recognized for many years. With it has come a realization that many dike-development tunnels do not have a permanent flow appreciably greater than that available from the springs representing the original drainage of the dike compartments. A considerable volume of records of the yield of dike tunnels, some of it coupled with the records of nearby spring flow and of pressures encountered behind dikes in tunneling, awaits analysis and correlation with rainfall records and studies of dike distribution. The results will be of great local value in the study of future tunnel results and also in the study of bulkheading to restore the storage capacities behind selected dikes, a practice that has been carried on to some extent in recent years but which has not been thoroughly analyzed.

The largest draft of ground water comes from basal bodies, generally floating on salt water, fed by direct recharge from the surface or by underground leakage from perched-water bodies or bodies impounded by dikes. Where the pervious lava flows containing this basal water extend to the coast without cover, the head of fresh water above sea level is small, increasing at the approximate rate of a foot per mile from the coast. Where, however, the seepage of fresh water to the ocean is restricted by a "cap" of less pervious sediments, as on much of Oahu, the head under and immediately behind the cap may be several tens of feet, higher in fact than the surface of the sediments in the belt close to the shore, thus creating artesian conditions. No lower limits to the zone of permeable lava flows are known or suspected within a range of several thousand feet below sea level for most of the basal aquifers.

The possibility of contamination of this basal fresh water by salt water was early recognized through experience and ascribed to the prox-

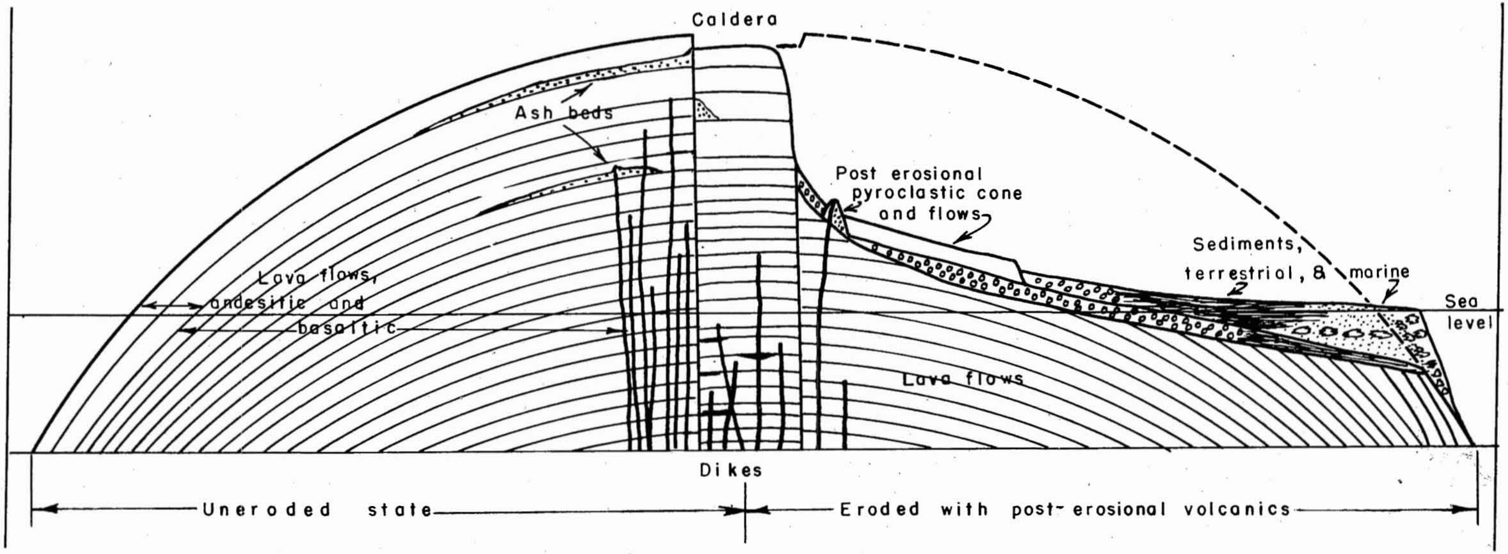

FIG. 1. Diagrammatic cross-section of a typical Hawaiian volcanic dome showing geologic structure.

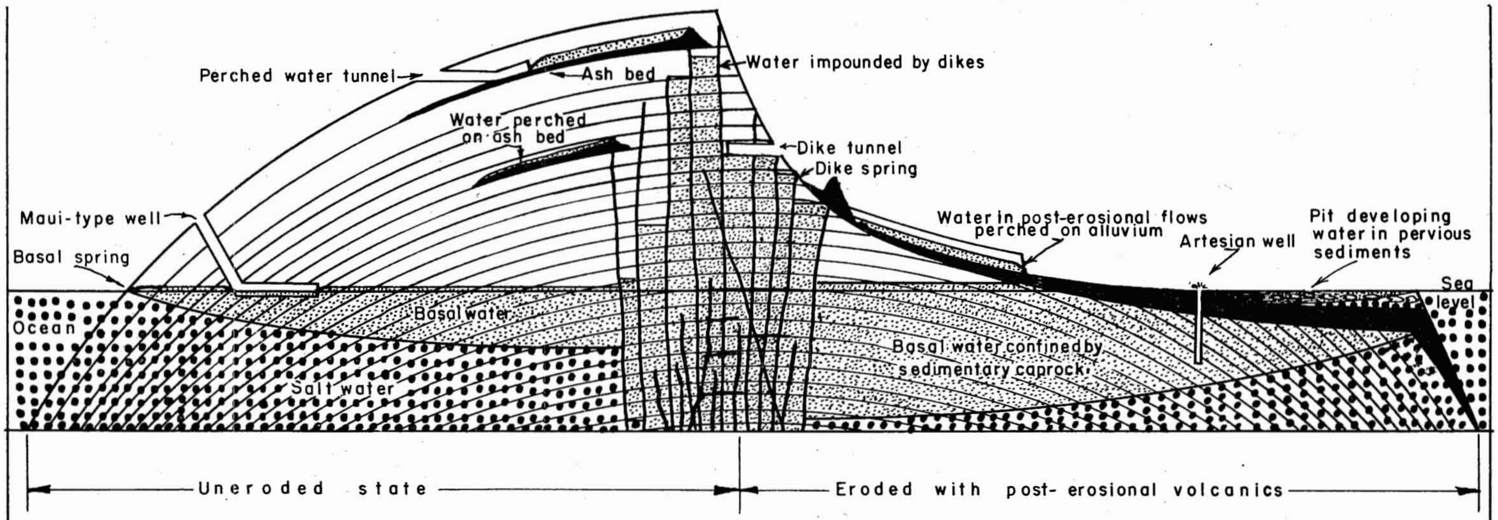

FIG. 2. Diagrammatic cross-section of a typical Hawaiian volcanic dome showing occurrence and recovery of ground water.

imity of the ocean. Before 1910, the floating relationship with underlying salt water was postulated (Stearns, 1935, Hawaii Div. Hydrog. Bul. 1: 256), but it was not until the late 1920's that the applicability of the Ghyben-Herzberg principle and its consequences were fully accepted (McCombs, 1927, U. S. Geol. Survey, Water-Supply Paper 596A; Palmer, 1927, Honolulu Board Water Supply, Sup. 1st Bien. Rpt.). According to this principle, the head of fresh water above sea level should be balanced by a depth of fresh water below sea level about 40 times as great, the exact ratio being dependent on the densities of the fresh and salt water. This relationship is correct only in static conditions, as has been demonstrated theoretically by Hubbert (1940, Jour. Geol. 28: 924–926), and requires modification in the near-shore area under dynamic conditions. Furthermore, it assumes steady-state conditions that do not pertain. As shown by Wentworth (1942, Amer. Geophys. Union, Trans. 23: 683–693), changes in the depth of the salt-fresh contact zone must lag greatly behind the changes in the water-table elevation that initiate them. As yet there is no theory expressing the lag in terms of the permeability and geometry of the aquifer and the nature of the fluctuation in head. The uncertainty is critical in attempts to estimate storage volumes and their changes.

Good records of many years or even decades of head variation exist for many aquifers, but the only indications of salt-fresh contact fluctuations lie in the voluminous records of salinity at wells, generally analyzed at random times without regard to the variation in pumping conditions. Though attempts have been made for several years now to collect salinity records under standardized conditions, there is still a further difficulty, pointed out by Wentworth (1947, Pacific Sci. 1(3): 172–184), that the available sampling points are all in the upper part of the zone of mixture, which is capable of varying in thickness as well as position.

At this point it would seem best to approach the whole problem from three directions simultaneously: (1) development of an adequate mathematical theory of Ghyben-Herzberg functioning under nonsteady dynamic conditions for simple cases; (2) checking and extension of the theory by models, very likely electrical analogues; and (3) further experimental checking from test holes penetrating the zone of mixture in the simplest Ghyben-Herzberg bodies available, for example, that on the isthmus of Maui, where there is practically no cap of sediments on the coast. The analysis of the experimental results in terms of the theory will depend on the measurement of permeability not only at the surface but also very deep in the aquifer. Fortunately, a method seems now to be available from the analysis of the progression of tide waves, induced by ocean tides, across the groundwater body (Cox and Munk, 1953, Amer. Geophys. Union, Trans. 34: 345).

The development of an adequate dynamic Ghyben-Herzberg theory will be of very great importance to an evaluation of basal groundwater resources in Hawaii. It will also be of importance in many other coastal areas where Ghyben-Herzberg conditions pertain and in some of which the problems of salt intrusion are critical, but where the development of theory is rendered difficult by the complexity of structure.—*Doak C. Cox, Experiment Station, Hawaiian Sugar Planters' Association, Honolulu, Hawaii.*